Effect of Impedance and Intrabeam Scattering on the BOOPI Scheme

—SRFEL-006—

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In SRFEL-003 and SRFEL-003a I presented simulations of acceleration with the Booster (BOO) of a photoinjector (PI) beam, which I call the BOOPI scheme. In this note, I extend those simulations to include the effects of longitundinal impedance and intra-beam scattering.

The longitudinal impedance model used here is a very simple broad-band resonator with Q=1. I only considered the longitudinal impedance for now. The resonance frequency was chosen to be $\omega = c/b$, where b is the "radius" of the beam pipe, taken as the vertical half-height of the elliptical chamber, or 3cm. I simulated this using the RFMODE element of elegant, which has been well-tested for this kind of simulation. I took $|\frac{Z}{n}|$ to be 1 Ohm, which is believed to be a conservative value for the booster. I didn't include transverse impedances.

For IBS, I used the IBS growth rate subroutine written by Louis Emery. In elegant, this subroutine is used to compute the IBS growth rates for x, y, and t motion on a turn-by-turn basis. In order to simulate the random nature of IBS, these growth rates are converted into sigmas for a ensemble of gaussian random numbers to be added to the x', y', and δ coordinates of each particle. I started with the simple equation

$$\Delta\epsilon = T_o \frac{d\epsilon}{dt}, \tag{1}$$

giving the change in emittance for a single turn, where T_o is the revolution time. Emery's IBS routine gives $\frac{d\epsilon}{dt}$ for the three planes.

If we represent the two phase-space coordinates by q (for x, y, or t) and p (for x', y', or δ), then the emittance squared is just

$$\epsilon^2 = \left\langle q^2 \right\rangle \left\langle p^2 \right\rangle - \left\langle qp \right\rangle^2 \tag{2}$$

Assuming that the p coordinate will be altered by the IBS algorithm, the change in ϵ^2 is just

$$\Delta\left(\epsilon^2\right) = \left[\left\langle q^2 \right\rangle \left\langle (p+\Delta p)^2 \right\rangle - \left\langle q(p+\Delta p) \right\rangle^2\right] - \left[\left\langle q^2 \right\rangle \left\langle p^2 \right\rangle - \left\langle qp \right\rangle^2\right] \tag{3}$$

Since Δp is uncorrelated with p and q, this reduces to

$$\Delta\left(\epsilon^2\right) = \left\langle q^2 \right\rangle \left\langle \Delta p^2 \right\rangle \tag{4}$$

Solving this for $\left\langle \Delta p^2 \right\rangle$ we have

$$\sigma_{\Delta p,IBS} = \sqrt{\left\langle \Delta p^2 \right\rangle} = \sqrt{\frac{\epsilon^2\left[(1+\frac{T_o}{\epsilon}\frac{d\epsilon}{dt})^2 - 1\right]}{\left\langle q^2 \right\rangle}} \tag{5}$$

This gives the widths of the distributions of gaussian random numbers to add to each of the coordinates in order to simulate IBS in the tracking.

The IBS feature of `elegant` was tested by simulating the APS storage ring with a 0.1nC bunch and full coupling. The tracking result was compared to iterative evaluation of the difference equations for the emittances (a computation which is performed by the commandline program `ibsEmittance`. I found close agreement between the two methods.

As in SRFEL-003 and SRFEL-003a, I simulated the ramping of the low-emittance booster lattice using 9 MV rf voltage starting at an energy of 450 MeV. The initial beam properties were a normalized emittance of 2 μm in both planes with hard-edge energy spread of $\pm$0.190 MeV and bunch length of $\pm$ 2.45 ps. Figures 1 through 3 show the evolution of the horizontal emittance, bunch length, and energy spread when various physical effects are included. Clearly the impedance is not an issue here, but just as clearly IBS has a dramatic effect.

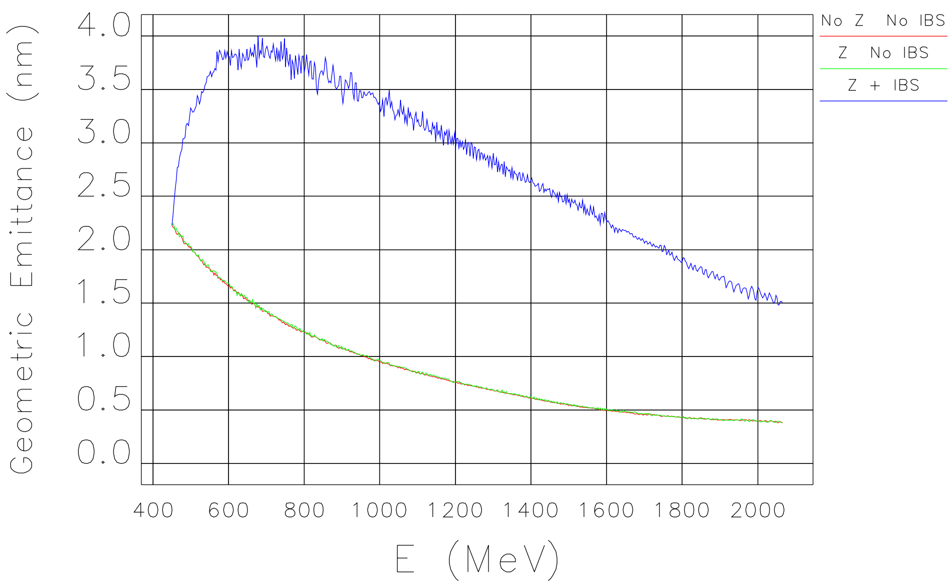

Figure 1: Comparison of the evolution of the horizontal emittance with different physical effects included in the tracking.

Figure 4 shows the performance of a SASE FEL using a 2cm period undulator with K of 1.879. The figure is based on the beam simulation with impedance and IBS included. One can see that the advantage of using the booster, to accelerate to higher energy and damp the beam adiabatically, is almost completely lost. While some acceleration is possible before the beam blows up, the parameter range is not promising.

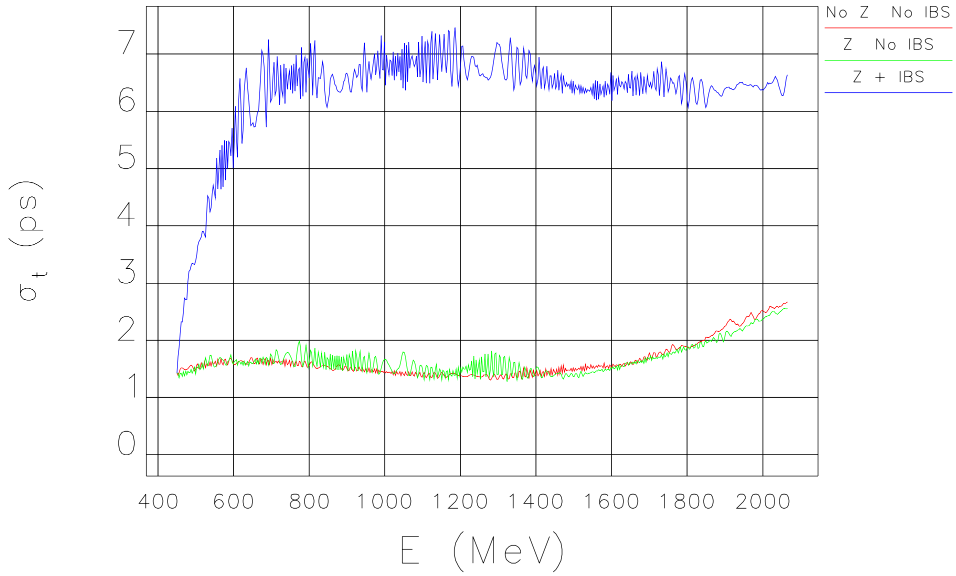

Figure 2: Comparison of the evolution of the bunch length with different physical effects included in the tracking.

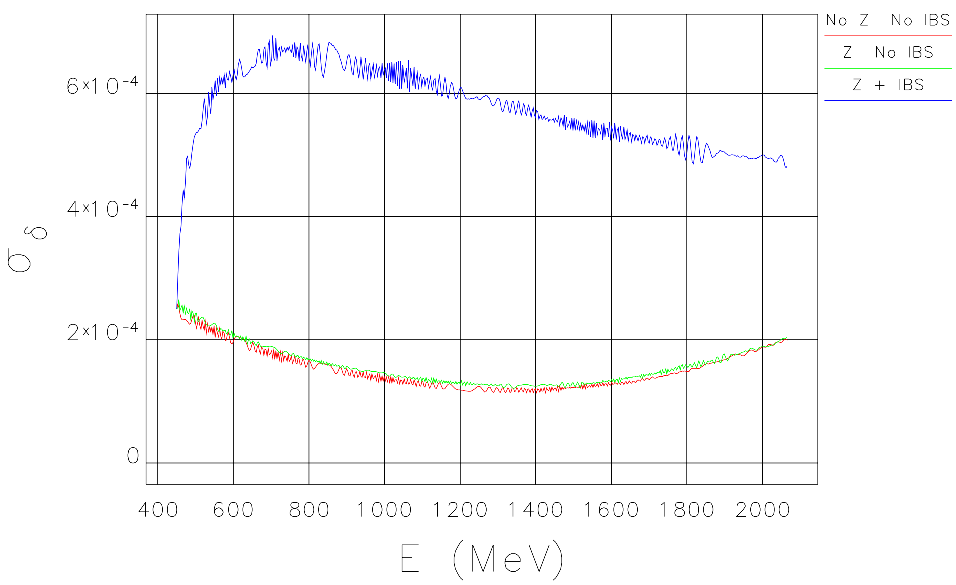

Figure 3: Comparison of the evolution of the energy spread with different physical effects included in the tracking.

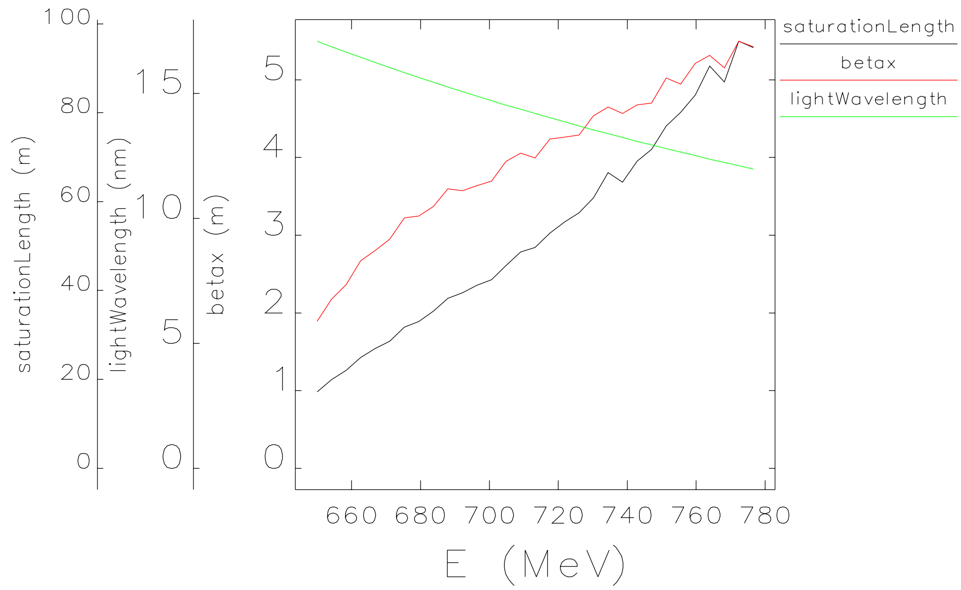

Figure 4: Performance of a SASE FEL when impedance and IBS are included in the booster simulation.